Groundwater

Rapid Communication/

Hydraulically Controlled Discrete Sampling from Open Boreholes

by Philip T. Harte

Abstract

Groundwater sampling from open boreholes in fractured-rock aquifers is particularly challenging because of mixing and dilution of fluid within the borehole from multiple fractures. This note presents an alternative to traditional sampling in open boreholes with packer assemblies. The alternative system called ZONFLO (zonal flow) is based on hydraulic control of borehole flow conditions. Fluid from discrete fractures zones are hydraulically isolated allowing for the collection of representative samples. In rough-faced open boreholes and formations with less competent rock, hydraulic containment may offer an attractive alternative to physical containment with packers. Preliminary test results indicate a discrete zone can be effectively hydraulically isolated from other zones within a borehole for the purpose of groundwater sampling using this new method.

Introduction

Groundwater sampling from open boreholes is particularly challenging because of mixing of fluid and dilution within the borehole from flow from multiple fractures (Figure 1A). The use of downhole pumps to extract groundwater or other fluids from long, open-hole bedrock wells is problematic because the well bore is a conduit that connects multiple fractures. The fluid sample from an open borehole is a flow-weighted mixture from multiple fractures. The unknown source origin of the resultant sample is less than ideal for the identification of natural and anthropogenic contaminant pathways.

Discrete fractures in an open borehole have been sampled by isolating intervals with packers (Shapiro 2002). However, the use of packers can be time consuming and logistically difficult. In formations with less competent rock, packers may not form effective seals. Discrete intervals also have been sampled passively with diffusion samplers that rely on ambient flow in an open borehole or well (Harte 2002; ITRC 2004). In many cases, the ambient flow provides a misleading picture of the contaminant distribution because flow is dependent on hydraulic factors and some zones of interest may not contribute any inflow to the well. Well liners are another method of sampling discrete intervals (Cherry et al. 2007) but equipment and deployment can be costly. Alternative sampling systems are needed to cover the entire range of conditions encountered in practice.

ZONFLO (zonal flow) is an innovative new sampling system that hydraulically isolates discrete zones in open boreholes. The sampling system couples hydraulic control of flow with dual tracking of vertical flow to extract fluid samples. Hydraulic control of flow is accomplished by use of a multiple vertically positioned pumps (Figure 1B and 1C). The absence of mixing is confirmed through dual flow tracking (either dual flowmeter logging or dual-tracer devices). The new sampling system, which a public-domain patent is pending, offers another tool for scientists and water managers interested in fine-resolution sampling (sub meter) in long-open boreholes and long-screened wells (many meters). This note describes the principle and operation behind the new system along with current limitations.

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Hydraulic Containment as a Sampling Strategy

Hydraulic containment has been used as a remediation strategy at groundwater contamination sites (Cohen et al. 1997) and is typically associated with altering large

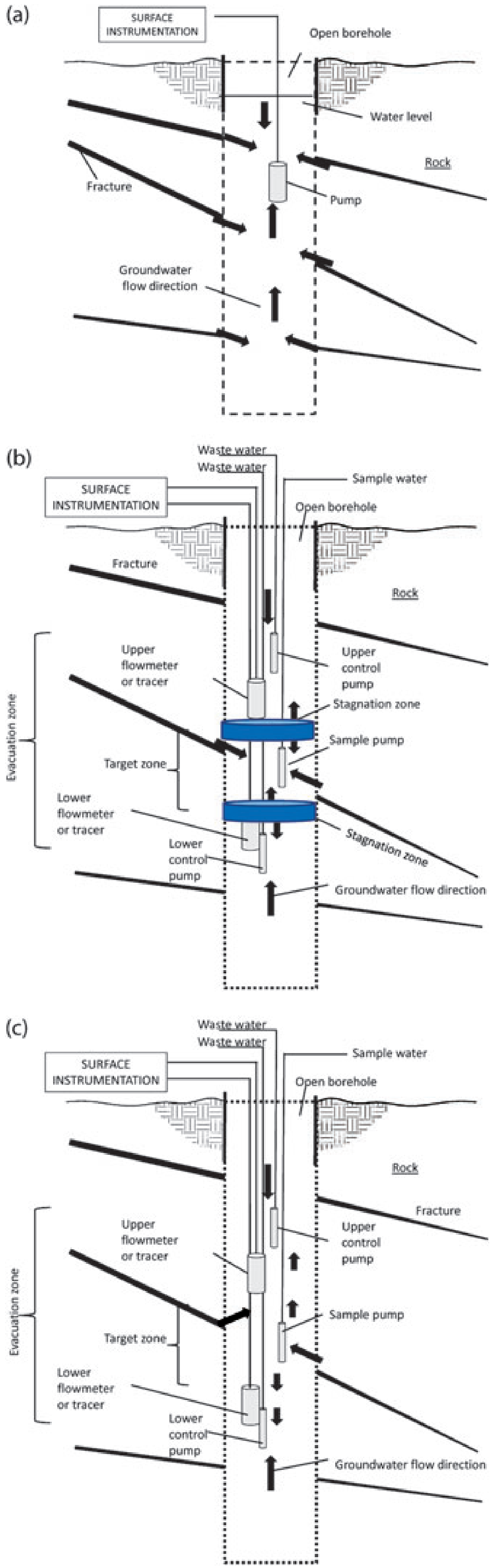

Figure 1. Vertical mixing of fluid within an open borehole (A), ZONFLO sampling under stagnation conditions (B), ZONFLO sampling under divergent conditions (C).

scale, three-dimensional flow fields in an aquifer (Ferris et al. 1962). However, extending the concept of hydraulic containment to smaller scales within a well bore allows for the ability to sample discrete zones and assess zonal transmissivity.

The ability to create hydraulic zones and boundaries from extraction using multilevel pumps within well bores is dependent on the distributional flow (the proportion of discrete flow per zone or fracture compared to the total flow of the open borehole or well screen) in the well and the well bore storage for unsteady state conditions. Distributional flow into the well can be measured by borehole flowmeter logging using various geophysical tools such as heat-pulse flow meters (HPFM). HPFM can be used to identify fractures contributing water to the well under ambient and pumped flow conditions (Paillet 2000). The distributional flow patterns in the well and the distribution of fractures for bedrock aquifers are the key determinants in the application of ZONFLO sampling.

Sampling Objectives and Principles

The primary objective during ZONFLO sampling is to hydraulically isolate groundwater within the target zone of interest (target sample zone) and to avoid sampling of groundwater from unintended parts of the borehole. This is achieved by the creation of either stagnation or minimal velocity flow zones between adjacent vertically positioned pumps or the creation of mildly divergent flow conditions (to avoid turbulence) away from the target zone. Two hydraulic containment (control) pumps extract well fluid above and below the target zone while a sample pump extracts well fluid from the target zone. The rates of extraction of the multilevel pumps are adjusted to create either stagnation or divergent conditions (Figure 1B and 1C). For stagnation conditions, the target sample zone is isolated based on volumetric balance between the net fracture flow into that zone, the rates of extraction of the sample pump and the control pumps, and the borehole flow (Table 1). For divergent conditions, the upper and lower control pumps are set at flowrates greater than the rate of the sample pump causing a predominance of vertical flow to move away from the target zone, excluding the fluid captured by the sample pump (Table 1). At

Table 1
Pump Rate Settings for Stagnation and Divergent Conditions

	Stagnation Conditions	Divergent Conditions
Upper flow zone (uz)	$Ucp = F_{uz}$	$Ucp \geq F_{uz} + (0.5 \times (F_{tz} - Sp))$
Target zone (tz)	$Sp = F_{tz}$	$Sp < F_{tz}$
Lower flow zone (lz)	$Lcp = F_{lz}$	$Lcp \geq F_{lz} + (0.5 \times (F_{tz} - Sp))$

Flz, flow from lower zone; Ftz, flow from target zone; Fuz, flow from upper zone; Lcp, lower control pump; Sp, sample pump; Ucp, upper control pump.

a minimum, the total pump rate for the control pumps must be twice as much as the sample pump to ensure divergent flow. For either condition, fluid extracted by the sample pump must be devoid of stagnant borehole fluid and recharged by fluid from the target zone. When initiating the pump sequence, the control pumps are turned on first to avoid mixing of water in the target zone.

Procedures

Prior to deployment of the ZONFLO system, conventional flowmeter logging (ambient and pumped) is performed to identify locations of fractures, their flow rates, and the total flow into the well (Hess 1982; Keys 1990). Optical or acoustic televiewer logs are performed to identify fractured and unfractured sections of the open borehole (Keys 1990). These data are used by ZONFLO, as with packer sampling, to identify target zones for sampling. Dual flow logging (using dual flowmeters under ambient and pump conditions) is recommended prior to ZONFLO to validate conventional flowmeter logging results and to assist in the identification of borehole flow. The dual flow logging method allows for synchronous vertical-flow measurements above and below the target zone. During ZONFLO sampling, extraction rates to the multilevel pumps are specified to match the distributional flow patterns observed during flowmeter logging (Table 1).

The borehole capture zone of the sample pump covers the target sample zone. The capture zone is constrained by the capture zones of the two hydraulic control pumps. The active evacuation zone is defined by the interval between the upper and lower control pumps.

The fracture distribution dictates ZONFLO configuration; namely the location of the targeted fracture relative to the next adjacent fractures. The length of the pumps (0.35 m) and flow-tracking devices (length varies based on tool) provide further constraints. The upper control pump is set 0.9 m (3 foot) or more above the sample pump to a maximum distance of 0.31 m (1 foot) below the upper fracture. The sample pump is positioned adjacent to the target fracture. The lower control pump is set at similar distances as the upper control pump. The dual flow-tracking devices are positioned between the control and sample pumps.

Hydraulic considerations also constrain the configuration such as the time required to evacuate stagnant borehole fluid. The distance between the control pumps (active evacuation zone) can be refined within the minimum and maximum constraints based on (Equations 1 and 2).

$$V_{(\mathrm{Qt})} = Bv \times V_{(\text{borehole storage})}, \tag{1}$$

and substituting the formula for volume of a cylinder and solving for D:

$$D = \frac{V_{(\mathrm{Qt})}}{Bv\pi\ (r_{\mathrm{w}} **2)} \tag{2}$$

where, D is the length of the evacuation zone, $V_{(\mathrm{Qt})}$ is the anticipated volume (V) extracted given the extraction rate (Q) and the desired time (t), r_{w} is the radius of well, and Bv is a predetermined evacuation amount as some multiple of the borehole volume. Shorter distances between control pumps results in quicker evacuation time.

Pump rates are manually adjusted to match the distributional flow of the well using variable controlled submersible pumps and precision needle control valves. Ultrasonic water meters are used to measure flow from the pumps. Drawdowns are continuously measured with a pressure transducer and data logger at 1 min intervals. Drawdown is checked against previous drawdowns from pumped HPFM logs to try to minimize differences.

Confirmation of favorable flow conditions is critical to ensure representative samples. Procedures include:

- dual (HPFM and electromagnetic [EM]) flowmeter logging,
- colloidal borescope,
- dual passive tracer devices, and
- borehole dilution logging.

The dual flowmeter tools are useful in measuring vertical flow. The HPFM has a lower velocity detection level (0.04 L/min) than the EM. The EM is also affected by electrical noise from the submersible pumps. The dual HPFM tools measure vertical flow independently but are mutually calibrated. The colloidal borescope identifies the trajectory of particles moving in the borehole fluid (Bayless et al. 2010) and is useful in the identification of differences resulting from the development of stagnation or minimal velocity zones between the pumps. The dual-tracer devices are coupled with continuous flourometer measurements at 1-min intervals using fluorometer probes and data loggers. Dual passive tracer devices were strategically deployed between the hydraulic control pumps and the sample pump to allow for tracking of vertical flow in the borehole. The tracers were placed inside porous bottles and frozen. Upon thawing downhole, the tracers seep out of the porous bottles without disturbing the flow field. For the dye used (Rhodamine-WT), diffusion transport is negligible over the testing period (h). The direction and rate of vertical flow are confirmed by tracking the presence of the tracers in the fluid extracted from the three pumps. The presence of the tracer in the control pumps confirms that flow is away from the target zone (no mixing of borehole water). Borehole dilution logging (Pitrak et al. 2007) involves pre-spiking the entire borehole with a tracer prior to ZONFLO sampling. A pre-ZONFLO dilution log is collected to confirm tracer disbursement in the borehole. During ZONFLO, the creation of a tracer-free zone in the target zone, as confirmed by monitoring of the extracted fluid from the sample pump, confirms that recharge of groundwater is occurring from targeted fractures. A post-ZONFLO dilution log is collected to map the extent of the tracer-free zone.

The chemistry of the fluid extracted from the sample pump and the control pumps is also monitored to aid in identifying fluid capture from the different zones in the well. These data provide additional evidence

Table 2
Distributional Flow from Conventional Pumped HPFM Log and Apportioned Initial Pump Rates of Targeted and Nontargeted Zones for ZONFLO

HPFM			ZONFLO		
Description of Measurement from HPFM Log	**HPFM (L/min)**	**Depth Below Top of Casing (m)**	**Configuration**	**Zone**	**Flow per Zone (L/min) (% of Flow)**
Total=	1.13			Total=	1.13
Pump position for conventional HPFM log	1.13	7.3		Upper	
Casing ends		30.2			
Flowmeter	1.13	30.5			
Flowmeter	1.13	35.7			
Inflow zone≫≫≫		36.0			
Flowmeter	0.49	36.3			(57%)
		45.4	**Ucp location**		0.64
		47.0	Dual flow-tracking location		
Flowmeter	0.49	47.6	**Sp location**	Targeted sample zone	(10%)
Inflow zone≫≫≫		47.9			0.11
Flowmeter	0.38	48.5			
		49.1	Dual flow-tracking location	Lower	
		49.7	**Lcp location**		0.38
Flowmeter	0.38	58.8			(33%)
Inflow zone≫≫≫		59.5			
Flowmeter	0.08	59.8			
Flowmeter	0.08	86.0			
Inflow zone≫≫≫		86.6			
Flowmeter	0.00	87.2			
Flowmeter	0.00	118.9			

HPFM, heat pulse flowmeter; Lcp, lower control pump; Sp, sample pump; Ucp, upper control pump.

to distinguish stagnant well bore fluid from recent fracture recharge. Continuous measurements at 1-min intervals of specific conductance and temperature are recorded with conductivity-temperature probes and data loggers.

After sample completion, the control pumps are terminated and borehole flow is re-measured. If dual-tracer devices are used, the detection of the dye in the sample pump after turning-off the control pumps confirms flow reversal in the evacuation zone and serves as further proof of hydraulic containment when the control pumps were operational.

Evacuation Requirements

Sample collection of the extracted fluid from the sample pump begins after evacuating a minimum volume of fluid (Equation 1) after confirmation of favorable flow conditions. A Bv (Equation 1) value of 2.3 is recommended when possible to allow for adequate evacuation of stagnant water (Barber and Davis 1987). The minimum extraction volume ensures the sample represents fresh recharge. Assuming favorable flow conditions, all of the fluid extracted by the sample pump is allocated toward meeting the minimum evacuation criteria whereas only a fraction of the fluid from the control pumps is allocated. The latter is calculated based on vertical velocity measurements from the dual vertical-flow-tracking devices.

Distributional Flow and Zonal Transmissivity

Rates of extraction during ZONFLO sampling are initially set to match the distributional flow pattern observed during conventional HPFM logging (Table 2) or the dual flowmeter logging. Table 2 shows an example of results from a HPFM log and the extraction configuration for a target sample zone of 47.9 m. The conventional pumped HPFM log identifies inflow zones based on net gains in vertical flow (Table 2). For the target zone of 47.9 m, the sample pump extracts no more than 10% of the total flow under the combined extraction rate of 1.13 L/min for the well. Most of the inflow (57%) occurs in the upper nontarget zone and to a lesser extent (33%) the lower nontarget zone.

If both drawdown and the formation of stagnation conditions are achieved, approximate values of zonal transmissivity can be computed from a simplified steady state radial flow equation for the upper, target, and lower zones (Equation 3):

$$T_{\text{zone}} = \frac{\left(Q_{\text{zone}} \times \ln\left(\frac{r_{\text{e}}}{r_{\text{w}}}\right)\right)}{2\pi s_{\text{w}}} \quad (3)$$

where T_{zone} is transmissivity of the zone, Q_{zone} is the extraction rate of the pump for that zone, r_{e} is the effective radius to the location of zero drawdown, and s_{w} is drawdown in the well. The parameter r_{e} is estimated to be 100 m. The expression $\ln(r_e/r_w)$ varies by a factor of 2 between r_e distances of 10 m and 1000 m and is relatively insensitive at these ranges. The zonal transmissivities are summed and checked against the well transmissivity to ensure reasonable zonal values. Drawdown and by extension head is assumed to be relatively uniform for the entire borehole; head differences in a typical borehole are probably less than 0.5 m given the extraction rates used, typical measured borehole velocities, and likely effective hydraulic conductivities of boreholes. Under transient conditions or divergent flow conditions, zonal transmissivity can be computed by numerical modeling of the observed borehole flow.

Field Demonstration

A field example that demonstrates the effectiveness of the ZONFLO system in isolating fracture water under divergent flow conditions is presented from a September 27, 2012 test (Figure 2). Dual passive tracer devices containing a Rhodamine-WT dye were placed between the hydraulic control pumps and the sample pump. The sample pump was placed adjacent to a fracture whereas the hydraulic control pumps were placed adjacent to unfractured parts of the rock above and below the sample pump. Pumped water from the hydraulic control and sample pumps were monitored for the presence of the dye. When the hydraulic control pumps were operational, dye was detected in their pumped water. During this time, the only dye present in the sample pump water occurred during the initial startup of the sample pump when the sample pump rates temporarily exceeded flow from the target fracture (Figure 2A). Figure 2B shows the period of time when the sample pump was effectively capturing "fresh" fracture water (fluorometer readings were at background levels). After approximately 1 h, the control pumps were turned off while the sample pump was kept operational and rates increased to an average rate of the control pumps. Under these conditions, dye was detected in the sample pump a few minutes afterward. The interpreted borehole flow pattern is shown in Figure 2C.

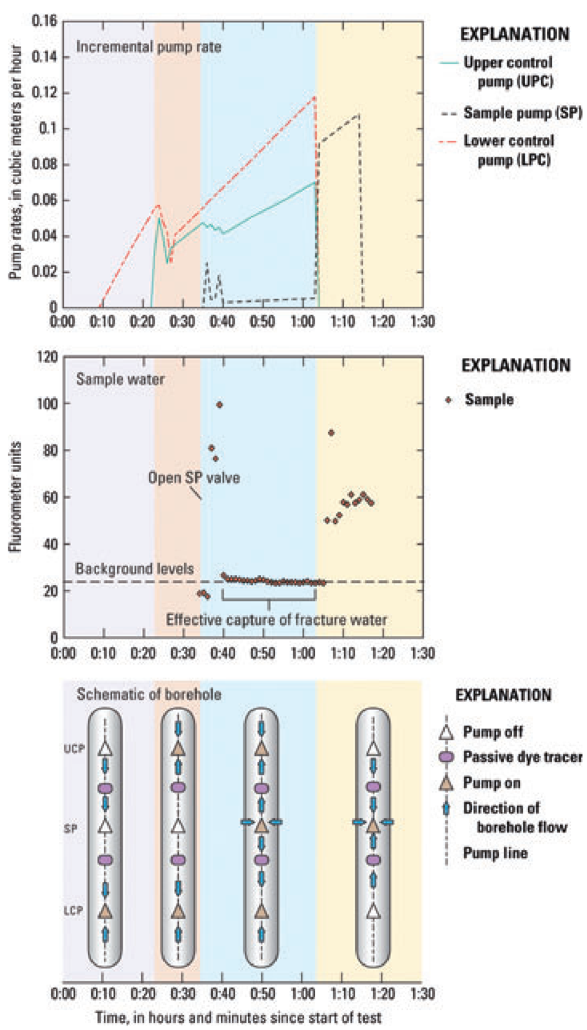

Figure 2. ZONFLO pump rates (A), continuous fluorometer measurements (B), and interpreted borehole flow (C) under divergent conditions.

Limitations

The ability of flowmeter logging to accurately delineate distribution flow is a potential source of error that may complicate hydraulic control and whether flow conditions can be stabilized during ZONFLO sampling. Specifically, the creation of stagnation conditions may be difficult to achieve, which would limit quantitative determination of zonal transmissivity using Equation 3. However, the creation of divergent conditions is less dependent on stabilization, which would still allow for the collection of representative discrete samples from the target zone.

Outflowing fractures under ambient conditions are problematic in ZONFLO sampling, as with other discrete sampling systems, because they tend to reflect a composite sample of the open borehole (Johnson et al. 2004). Flows can be reversed by targeting these fractures for sampling but the sample still represents a mixed sample that is affected by previous outflowing conditions. Further, if outflowing fractures are produced during pumped HPFM logging, then these fractures cannot be sampled with ZONFLO unless pumping rates are increased and flows reversed. Additional HPFM logging would need to be collected under the increased pumping rates prior to ZONFLO sampling to define the new distributional flow pattern.

Hydraulic limitations exist based on the pumps deployed, drawdown, flow from fractures, and depth. The pumps deployed have a performance range of 0.95 L/min (0.25 gpm, 0.057 m^3/h) to 13.26 L/min (3.5 gpm, 0.794 m^3/h). The addition of precision needle valves allowed rates to be set as low as 0.048 L/min (0.013 gpm, 0.003 m^3/h). Hydraulic isolation requires that fracture inflow from nontarget zones not exceed the pump rate of the control pumps. It is possible to obtain representative samples if inflow from the target fracture exceeds the sample pump as long as the control pumps are hydraulically containing inflow from the nontarget zones and inducing divergent conditions from the target zone. Drawdown cannot exceed 61 m (200 foot). Currently, the system has an effective sample depth of less than 122 m (400 foot).

To date all wells tested consisted of 152 mm (6 inch) diameter open holes, which allowed for the deployment of multiple downhole devices. Testing in small diameters may present deployment problems and also induce higher fluid velocities above a laminar flow threshold (to avoid mixing). Testing in large diameters will require larger volumes of fluid to be extracted, which would prolong sampling.

The specific capacity of wells that have been tested ($<$1.15 L/min/m, $<$1 gpm/ft) is representative of values reported for monitoring wells and domestic-supply wells in crystalline-rock aquifers of New England (Hansen and Simcox 1994). The use of ZONFLO in highly productive wells may not be possible given the constraints described above. Further at waste sites that require containerization of extracted fluid, high yielding wells could present fluid disposal problems.

Conclusion

Fractures can be isolated hydraulically and sampled discretely with ZONFLO under favorable hydraulic conditions, such as appropriate fracture inflow rates (the current maximum rate is 13.3 L/min). ZONFLO is an alternative to traditional packer-based sampling systems and does not require the use of cable tools and rigs. Therefore, deployment can be quicker than traditional packer-based sampling systems. Hydraulic containment is likely to be less affected by rough irregular surfaces in open boreholes that have undergone hydraulic fracturing than physical containment systems; thus, hydraulic containment offers discrete sampling capabilities where packers may fail. The new system offers another tool to scientists and water managers who are tasked with the challenge of identifying contaminant pathways and sources in complex fractured-rock aquifers or heterogeneous unconsolidated aquifers.

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